Beam-Dynamics Discussion

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The beam-dynamics discussion centered on three questions:
- What modes of plasma focusing can be used on NDCX-II?
- What beam-dynamics experiments can be carried out on NDCX-II?
- What experiments can be done in collaboration with other ion-beam groups?

Plasma Focusing

The plasma-focusing discussion began with Erik Gilson reviewing his own work on the NDCX Ferro-Electric Plasma Source (FEPS). He pointed out that the number density range for a FEPS plasma is 10^{10} - 10^{12} cm^{-3}, depending on the ceramic material used. This range remains greater than the expected density of the NDCX-II beam up to the final ~20 cm of drift-compression. If higher plasma densities are needed, however, improvements in the electrode design and pulse-power circuitry are expected to increase the FEPS plasma density by an order of magnitude. The VNL might also investigate the flashboard sources being developed by Dr Krasik of Techion Israel. These sources, which can produce plasma densities up to 2 x 10^{13} cm^{-3}, are printed on a plastic substrate that can be bent into a cylinder. The gas pressure for these sources is about 10^{-5} Torr, which may allow the plasma to be produced as much as 5 m away from the transport line.

Igor Kaganovich began a presentation on beam focusing by observing that a neutralizing plasma can be introduced radially in an unmagnetized transport section but must be introduced along field lines in a magnetized region. An ion beam can drag along electrons as it passes from a neutralizing plasma into a vacuum, but in this process, the electrons acquire a velocity spread up to twice the average beam velocity. Several types of plasma lenses were discussed. A Gabor lens uses cylindrical electrodes and a solenoidal magnetic to confine cold electrons in a rigid-rotor equilibrium, satisfying the Brillouin-flow condition $2\ \omega_{pe}^2 = \Omega_{ce}^2$, where ω_{pe} is the electron plasma frequency and Ω_{ce} is their cyclotron frequency. An ion beam passing through this electron distribution feels a focusing force that is proportional to the electron density. A Robertson lens differs from a Gabor lens in that (1) the incident beam is already space-charge neutralized and (2) the surplus of electrons needed along the beam axis is produced by a magnetic field squeezing the neutralizing electron radially rather than by prefilling. The collective focal length is then the geometric mean of the focal lengths of the two species calculated independently. The Morozov lens is another variant of this approach, using ring electrodes in the plasma to ensure that magnetic surfaces are electrostatic equipotentials. For these plasma lenses and for conventional focusing solenoids, there was some audience concern about fringe magnetic fields affecting the behavior of HEDP targets. Alex Friedman commented that it may be necessary to design a flux return path into the final-focus solenoid to minimize the extent of fringe fields. He also mentioned that the problem of getting plasma across field lines might be addressed by using magnetic cusps, allowing injection along field lines.

Mikhail Dorf made a presentation covering three topics. (1) He observed that whistler waves can be used to diagnose a beam. Such waves can be produced by deliberately changing the B_z field and hence the cyclotron frequency of beam ions, with the frequency being determined by the Cherenkov condition. Such waves could be detected by magnetic loops. (2) He reminded the group of the enhancement of self-focusing when $\Omega_{ce} >> \beta_b \omega_{pe}$, where β_b is the average beam velocity scaled by the speed of light c. This enhancement requires a longitudinal magnetostatic field, which, as Alex Friedman pointed out, is not planned for the NDCX-II drift-compression section. (3) The requirements for collective focusing on NDCX-I and NDCX-II were also compared, showing that the effect would be small in NDCX-I experiments, due to the small beam velocity, but could be significant on NDCX-II if a 900-G field were added during drift-compression. Alex Friedman proposed designing the NDCX-II drift-compression section to allow for application of a flexibly tailored B_z field, enabling experimental verification of the self-pinching discussed during the presentation and permitting addition of a Morozov lens.

There was discussion about mitigating the effects of electrons streaming from the target into the solenoids, due, for example, to the beam prepulse interacting with the target. These electrons can replace electrons dragged along with the beam, thereby preventing the collective focusing effect Mikhail Dorf discussed. Regarding the effect of prepulse electrons, Larry Grisham commented that a negatively biased ring protected by a grounded shield has been successfully used with MFE ion beams to control the backflow of electrons.

Dynamics Experiments

Dave Grote made a short presentation on his work with the Warp code to optimize the NDCX-II acceleration schedule and to determine the sensitivity to errors in solenoid alignment and pulsed-power timing. He also discussed his observation that a 15-T final-focus solenoid can increase the minimum length of the very short NDCX-II beams, due to the different gyroradii of ions entering the solenoid at different radii. This purely kinematic effect has not been seen on NDCX-I because of the longer pulses and weaker final-focus solenoid. Plots showing the final NDCX-II beam current and longitudinal phase space caused some confusion, due to the long but very low-current longitudinal halo that was exaggerated by the graphics. Igor Kaganovich observed that the initial 100 V beam temperature in Warp was set arbitrarily rather than being based on measurements, but Dave argued that the value was insignificant compared with other sources of longitudinal temperature. Alex proposed deliberately introducing alignment errors in NDCX-II to test sensitivity and to validate the computer models.

Irv Haber made a presentation on recent results from the University of Maryland electron ring UMER. With longitudinal confinement, that experiment has transported its beam for up 1000 turns, corresponding to 36,000 lattice periods. Other achievements by the group have been the successful use of phase-space tomography and the development of a transverse-halo diagnostic with high dynamic range. The low energy of UMER, however, makes the experiment uncommonly sensitivity to distortions in Earth's magnetic field due to nearby conductors.

The question of whether secondary electrons pose a problem in NDCX-II was discussed briefly. Early simulations by Ron Cohen and Dave Grote indicate that the acceleration gaps prevent electrons from following the beam, so little further attention has been paid to this question.

Steve Lund made a short presentation about whether einzel lenses could be used upstream both to compensate for the chromatic aberration resulting from the final head-to-tail variation in the NDCX-II beam velocity and to correct defocusing effects in the bunching module. The conclusion of the numerical study was that designing such einzel lenses is difficult due to time-dependant defocusing effects that result from the necessary temporal voltage variation on einzel-lens electrodes.

Collaborations

Although no one from GSI was present, some participants discussed experimental questions that could be addressed by the groups at PPPL and the University of Maryland. Alex Friedman said that UMER has already proved useful in benchmarking Warp. He suggested, in addition, that the UMER halo diagnostic might prove useful on NDCX-II and that the Maryland machine might be used to look both at the beam lengthening in a strong solenoid mentioned by Dave Grote and at the long-standing question of coupling between transverse and longitudinal waves. Separately, Alex suggested that the Princeton group could investigate the use of a gas-puff diagnostic or laser-induced fluorescence of the beam itself to replace scintillators. Larry Grisham commented that laser-induced fluorescence could conceivably work on alkali-metal beams like Li^+ in NDCX-II

General Comments

Scattered comments touched on topics outside the main discussion areas.

- Steve Lund pointed out that the extreme compression required in NDCX-II is quite unlike what is needed for an HIF driver. Alex Friedman responded by saying that the program nonetheless profits from having short-term goals and that HEDP questions are themselves interesting. This view was seconded by Mark Koepke.

- Irv Haber mentioned that past experiments have encountered problems using short solenoids due to the difficulty distinguishing the effects of tilts and displacements.

- Dave Grote pointed out that Warp has not yet been used to explore the sensitivity of NDCX-II to non-uniform emission from the beam source. Irv Haber added that source alignment and emission can change faster than lattice alignment and can introduce larger errors. This area will be investigated later in 2010.

- A question about the reconfiguarability of NDCX-II led to a discussion of plans after the baseline accelerator is complete. There was general agreement that the highest priority is adding cells to boost the final beam energy above the Bragg peak for Li^+ stopping in aluminum, about 1.9 MeV. Alex Friedman suggested that effective use of all fifty available cells will require rethinking the choice of ion and the acceleration schedule, due to the increase of ion range with energy.